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DUCT MODE MEASUREMENTS ON THE TFE731-60 FULL SCALE ENGINE

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Abstract

A continuously rotating rake with radial microphones was developed to measure the inlet and exhaust duct modes on a TFE731-60 turbofan engine. This was the first time the rotating rake technology was used on a production engine. The modal signature for the first three fan harmonics was obtained in the inlet and exhaust. Rotor-stator and rotor-strut interaction modes were measured. Total harmonic power was calculated over a range of fan speeds. Above sonic tip speed, the rotor locked mode was not strong enough to be identified, but the "buzz-saw" noise at fan sub-harmonics was identified.

Introduction

The Advanced Subsonic Technology (AST) program sponsored the Engine Validation of Noise Reduction Concepts (EVNRC). A full-scale turbofan engine, the TFE731-60 was used as a test bed for part of this program. A continuously rotating rake with radially distributed microphones was developed for use on the Honeywell TFE731-60 as an acoustic diagnostic tool. Rotating rake technology had been developed and used successfully on model scale¹ and a dedicated test bed.² The test was accomplished in two separate, repeated, entries during June and August 1999.

Experimental Apparatus

TFE731-60 Turbofan Engine

A TFE731-60 engine with accompanying reference inlet and nozzle was used for this test. Basic engine information is described in table 1. The TFE731-60 has 22 rotor blades and 52 stator blades. The rotor-stator interaction mode at blade passing frequency (BPF) is cut-off below sonic rotor tip speed. The engine was tested at the Honeywell engine test stand in San Tan,

Arizona. A photograph of the engine on the test stand, and a schematic of the fan flow-path are shown in figure 1.

Rotating Rake

Methodology

The classic paper by Tyler and Sofrin³ presents the theory of fan-duct mode generation and propagation. The generation of circumferential spinning modes is governed by the following equation:

$$m = sB \pm kV \quad (1)$$

where

m = circumferential mode number

s = harmonic index

B = number of rotor blades

k = an integer (0,1,2,...)

V = number of stator vanes

The rotor locked, or rotor alone, mode ($m=sB$) spins at the shaft rotation speed. It is the potential field of the rotor. Separate rotor-stator and rotor-strut interaction modes also exists at the same m-order, when $k=0$. These modes, and higher order modes, can only propagate in a narrow annular duct if the blade tip speed which correspond to their spin rate is above Mach = 1.0. Lower order modes, which spin faster, may propagate if their spin rate results in sonic speed. The critical tip Mach number is slightly greater than 1.0 for non-narrow annular ducts. The spin rate of a circumferential mode is determined by the following equation:

$$\Omega_m = sB\Omega/m \quad (2)$$

where:

Ω_m = mode rotation speed

Ω = shaft rotation speed

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Each circumferential mode, m , can have one or more radial modes, n . Mode propagation is dependent on the cut-off frequency, which is unique to each (m,n) mode. This frequency is dependent on geometric parameters and the eigenvalue of a combined Bessel function that is a solution to the cylindrical wave equation. Below the cut-off frequency the mode will decay exponentially. Above cut-off, propagation occurs and acoustic power is transmitted down the duct and into the farfield. The cut-off frequency is given by:

$$f_{co} = \hat{e}c/\pi D \quad (3)$$

where:

f_{co} = cut-off frequency
 \hat{e} = bessel function eigenvalue
 c = speed of sound
 D = duct diameter

The Bessel function eigenvalue incorporates the duct geometry effects. The cut off ratio gives the ratio of the mode frequency to its cut-off frequency.

$$\zeta = f/f_{co} = \pi s B(\Omega m) D / 60 \hat{e} c \quad (4)$$

The rotating rake instrumentation system provides a complete map of the duct modal signature at 1BPF, 2BPF, and 3BPF (blade passing frequency) for either the inlet or the exhaust duct.⁴ The resolution of circumferential modes arise from a Doppler induced frequency shift due to the unique and discrete rotation rate of each m -order imparted by the continuous rotation of the rake.⁵ Radial modes are computed from a least squares data fit of the radial pressure profile using the hardwall Bessel functions as the basis functions.⁶

The modal data from the rotating rake are presented in 3-D format. The base plane axes are m - and n -order, and the vertical value axis in the PWL in the (m,n) mode. Along the wall of the m -order axis the sum of all the radials provides the power in that circumferential mode. The sum of all provides the PWL in the harmonic presented. A typical modal decomposition provides information as to the dominant modes present, usually those due to the rotor stator interaction. Of secondary interest will be other modes, which may be due to inflow distortions or other geometric disturbances.

The circumferential rotor-stator interaction modes for the first three blade passing frequencies are presented in table 2a. In addition, there are 10 downstream exhaust struts that could produce Tyler-Sofrin type interaction modes shown on table 2b.

Hardware

The rake acquires pressure data as it spins around the nacelle using a series of radially distributed pressure transducers pointing at the fan. The rake is used in two

locations—the inlet and the exhaust. The inlet rake rotates around the duct centerline inside the nacelle at the throat. At the nozzle, the rake rotates at the exit plane of the bypass duct. Photographs and schematic drawings of the rakes are shown on figure 2. The rotating parts are shown in red while the stationary parts are blue. Both rakes have windscreens covering the transducers to: lower vortex shedding noise from the inlet rake; and lower interaction with the viscous wake for the exhaust rake.

The rotational speed of the rake was required to be a specific whole number fraction, i.e., 1/200 in this case, of the TFE731-60 fan shaft speed and in phase with the shaft. This means that when the fan has rotated 200 times, the rotating rake will have completed exactly one revolution in that time span within $\pm 0.2^\circ$. This speed and phase synchronization is necessary in order to resolve the Doppler induced frequency shift of the spinning acoustic modes. Consequently, the rake requires a very accurate drive and control system. This accuracy must also be repeated over the entire test period (five to ten minutes) without build-up of phase error. The rake must follow the fan precisely even though the fan will wander in speed (5 to 10 rpm or so) throughout the test period. Consequently, the rake drive system must be slaved directly to the fan. Table 3 contains a list of rake control system performance requirements.

The inlet installation was a design challenge, since the whole rotating rake mechanism had to fit inside the Inflow Control Device (ICD). An ICD is used to eliminate the ground vortex and reduce the incoming atmospheric turbulence thus simulating in-flight noise during static testing.

Test Conditions

Rotating Rake measurements were taken over a fan speed range of approximately 6000 to 10000 rpm. Nominal data points were taken at 60, 64, 67, 75, 81, 88, and 94 percent of $N1C_{max}$. The TFE731-60 is a geared fan with a ratio of 2.0645 so that $N1C_{max}$ corresponds to $N_{f_{max}} = 10,172$ rpm; $V_{tip} = 1362$ fps. Approach is 64 percent $N1C$ ($V_{tip} = 872$ fps), cutback is 81 percent $N1C$ ($V_{tip} = 1104$ fps). Due to operational constraints 81 percent was not achievable; 78 percent $N1C$ was substituted. Points at 88 percent and above represent supersonic rotor tip speeds.

Two entries, separated by a major configuration change, were tested. A major difference between the two entries was that for the first entry the engine was side mounted, allowing the engine to pitch up with increasing thrust, causing the rotating rake to no longer rotate about the engine centerline. This may have caused an inaccuracy in the inlet measurements due to

positioning error, which was not quantified. For the second entry, the engine was top mounted, reducing the pitch-up with thrust considerably.

Results and Discussion

The complete mode map (circumferential and radial) for the inlet and exhaust ducts for the first blade passing harmonic at 60% N1C are shown on figure 3. The measurement noise floor is estimated to be about 95 dB. The inlet modes are dominated by the co-rotating (positive) spinning modes. This is because the contra-rotating modes are blocked by the rotor.⁷ The exhaust mode distribution is more uniformly distributed between the co- and contra-rotating modes. The overall PWLs are 114.8 in the inlet, and 115.2 dB in the exhaust. While the rotor-stator interaction mode is cut-off at BPF below sonic rotor tip speed, the rotor-strut-modes are cut-on. These strut modes are identifiable, but their contribution to the overall PWL is minor as can be seen by comparing the sum of the strut mode PWL to the overall PWL.

The m-order distribution for the high speed (88 percent N1C) is shown on figure 4. (The complete mode-map is available, but the density prevented meaningful display.) At this speed, the rotor locked mode ($m=22$) is cut-on. The inlet shows the increase in the $m=22$ and the neighboring modes. Recall that the $m=22$ mode is actually the sum of the rotor-locked mode, the rotor-stator interaction mode ($k=0$), the rotor-strut interaction mode, and the rake wake interference mode. The exhaust shows a general increase in all modes with the rotor-strut interaction modes showing a modest dominance over the non Tyler-Sofrin interaction modes, or extraneous modes.

Figure 5 summarizes the strut modes and the total harmonic power levels versus %N1C for BPF. In the subsonic tip regime, the PWL is dominated by the sum of the extraneous modes. The cut-on of the $m=22$ modes above a sonic tip speed contributes to a 15 dB increase in the overall PWL.

Figure 6 shows the m-order distribution for 2xBPF for 60 percent N1C. The rotor-vane interaction is the $m=-8$. This mode is almost 10 dB higher than the other modes, though in the inlet it is considerably lower due to rotor blockage. At the 88 percent N1C, (figure 7), the inlet shows a strong $m=-14$ and $m=+14$. Though the $m=+14$ is a strut mode, neither mode is strongly present at other speeds. In general, the rotor-strut modes at 2BPF do not rise above the extraneous mode levels.

Figure 8 shows that at 2BPF the PWL is exhaust dominated by 5 to 10 dB. In the exhaust, the rotor-vane interaction mode is a significant contributor to the overall PWL, only 3 to 6 dB below. The second

harmonic of the rotor-locked mode ($m=44$) is not significant.

The two separate test entries, separated by a major configuration change, allowed for a determination of the repeatability of the mode measurement technique. Figure 9 shows the repeatability for two runs for each entry. The BPF rotor-strut-interaction modes agree to within a few dB. For the strong rotor-vane interaction mode at 2BPF, the m-order repeatability is within 1 dB. The individual radials show good repeatability with the stronger radials demonstrating closer agreement. Other speeds demonstrated similar repeatability.

The rotor-locked mode ($m=22$ at BPF) cuts on at 8341 rpmc. As discussed before, this mode is contaminated by the rake-wake rotor interaction. For the subsonic rotor speeds the rake-wake rotor interference which shows up at $m=22$ is the only mode that should be measured at $m=22$. Therefore it may be possible to draw a qualitative conclusion about the rotor-locked mode by comparing the levels of $m=22$ above and below cut-on as in figure 10a. Since the $m=22$ mode changes very little as the rotor-locked is cut-on it is assumed that what is being measured by the rake is mostly the interference mode, and that the rotor-locked mode is not distinguishable from the interference. For comparison, the $m=22$ mode measured in exhaust is shown, and the clear increase as the combined modes at $m=22$ is observed. (There is no rotor wake contamination with the rake in the exhaust.)

The lower shaft-orders (21,20,19...1) also contribute to the "buzz-saw" noise generated near sonic tip speed. The mode generated at each shaft-order is numerically identical, i.e., at the 20th shaft order the $m=20$ mode is generated. Figures 10b and 10c show m-order contribution for all shaft orders below BPF. The highest levels occur at shaft-orders 11 to 15. As a result of the eigenvalues, at the lower shaft-order/m-order (so/m) the cut-off ratio actually decreases, to the point that for so/m 13 and below the mode is classically cut-off. This is part of the reason for the mode pressure rise at so/m = 14. However, Mach number effects cause propagation of these lower shaft-order/m-orders.

Conclusions

The first Rotating Rake mode measurements were taken on a full-scale turbofan engine, the TFE731-60. The rotor-strut interaction modes at BPF were identified as the dominant modes but were to be a minor contribution to overall PWL, due to the strength of the extraneous (background) modes. Rotor transmission losses were shown to result in lower co-rotating modes in the inlet. The 2BPF rotor-vane interaction mode was clearly identified in the inlet and exhaust, and observed to dominate.

Repeatability of the measurements was shown to be excellent by comparing results from two separate test builds.

An attempt to measure the rotor-locked noise was inconclusive though some information showed the sub-harmonics ("buzz-saw") to be dominated by the shaft-orders just under 1/2 BPF.

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Table 1. TFE731-60 engine parameters

Basic Engine Weight	988 lb
Takeoff, Sea Level, Static Thrust	5000 lb
Airflow	187 lb/sec
Cruise Bypass Ratio	3.9
Cycle Pressure Ratio	22
Geared Fan Pressure Ratio	1.70

Table 2a. Rotor-stator interaction modes

Harmonic	Interaction modes
1BPF	2*
2BPF	44,-8
3BPF	66,14

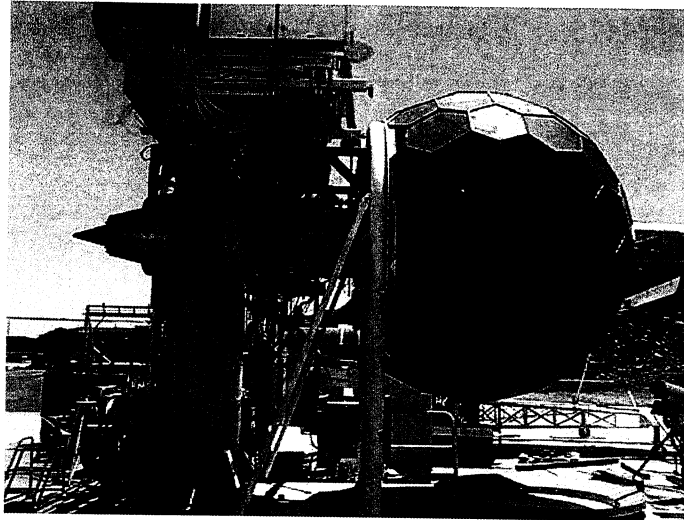
*cut-off at subsonic speeds

Table 2b. Rotor-strut interaction modes

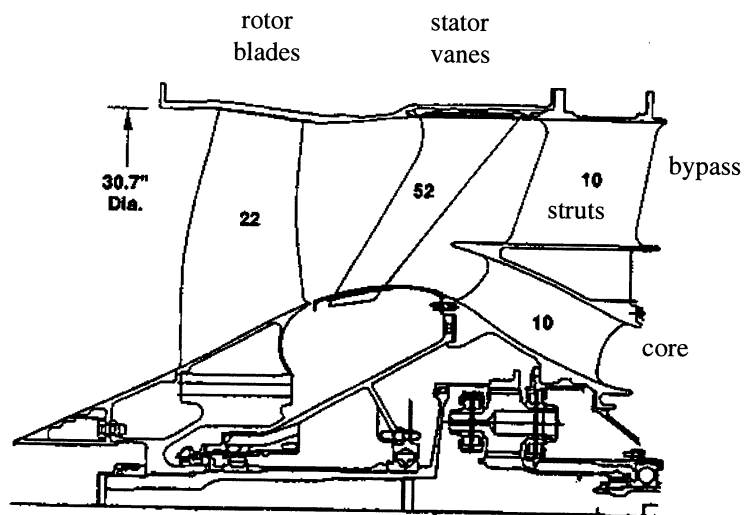
Harmonic	Interaction modes
1BPF	22,12,2,-8,-18
2BPF	44,34,24,14,4,-6,-16,-26,-36
3BPF	66,56,46,36,26,16,6,-4,-14,-24,-34,-44,-54,-64

Table 3. Rake design parameters

Maximum fan speed	10,000 rpm
Rake speed ratio	1/200
Maximum rake speed	50 rpm
Accuracy of fan-following rake speed	$\pm 0.2^\circ$ of rake rotation
Test point duration	10 minutes
Number of microphones	Inlet: 14 Nozzle: 8
Max duct flow (M#)	Inlet: 0.60 Nozzle 0.85

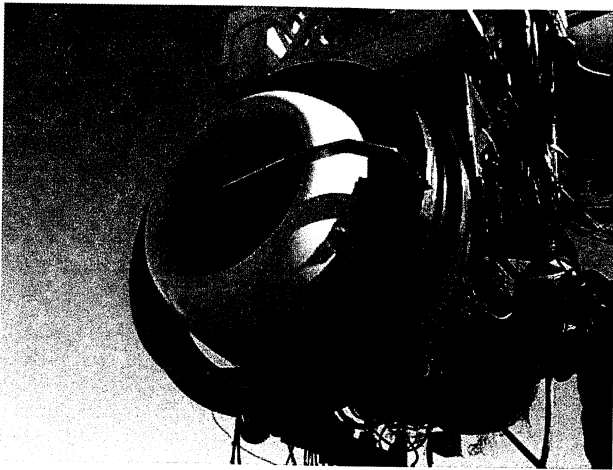


(a) Photograph of TFE731-60 engine on Honeywell test stand

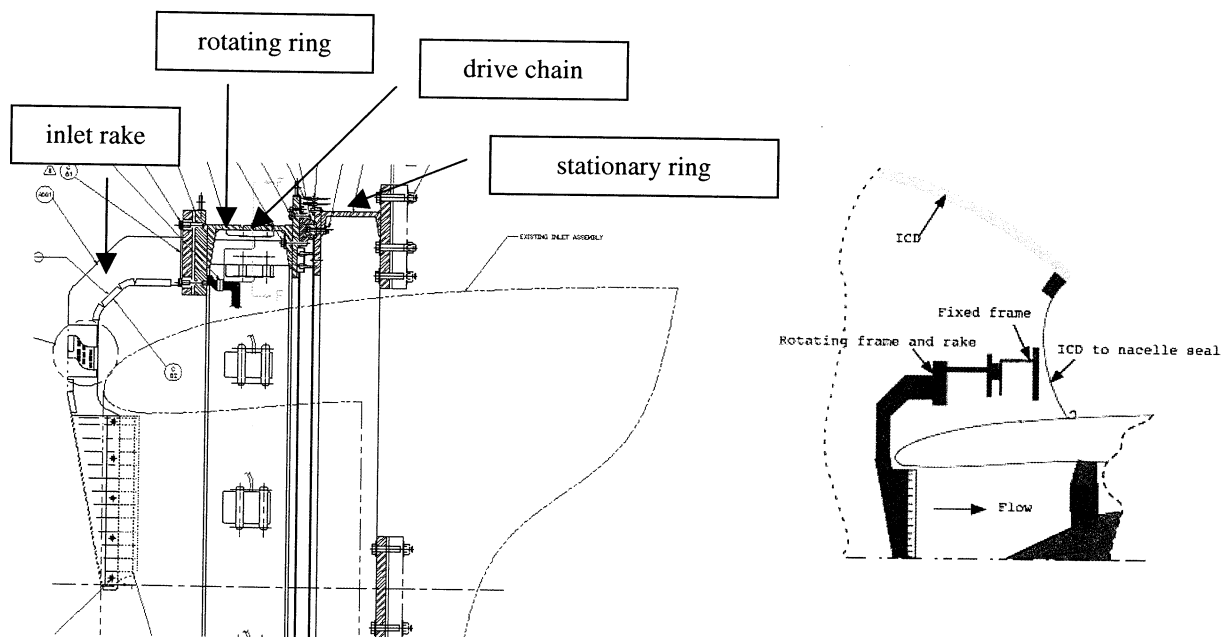


(b) Schematic of fan flow-path

Figure 1. Honeywell TFE731-60 Engine

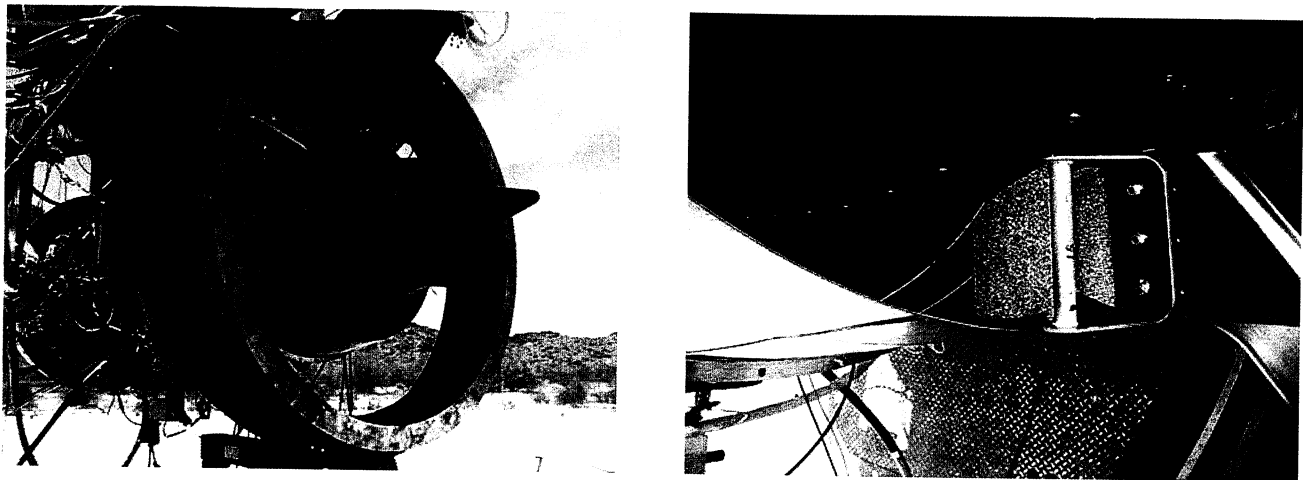


(a) Photographs of inlet rake installed on TFE731-60 engine

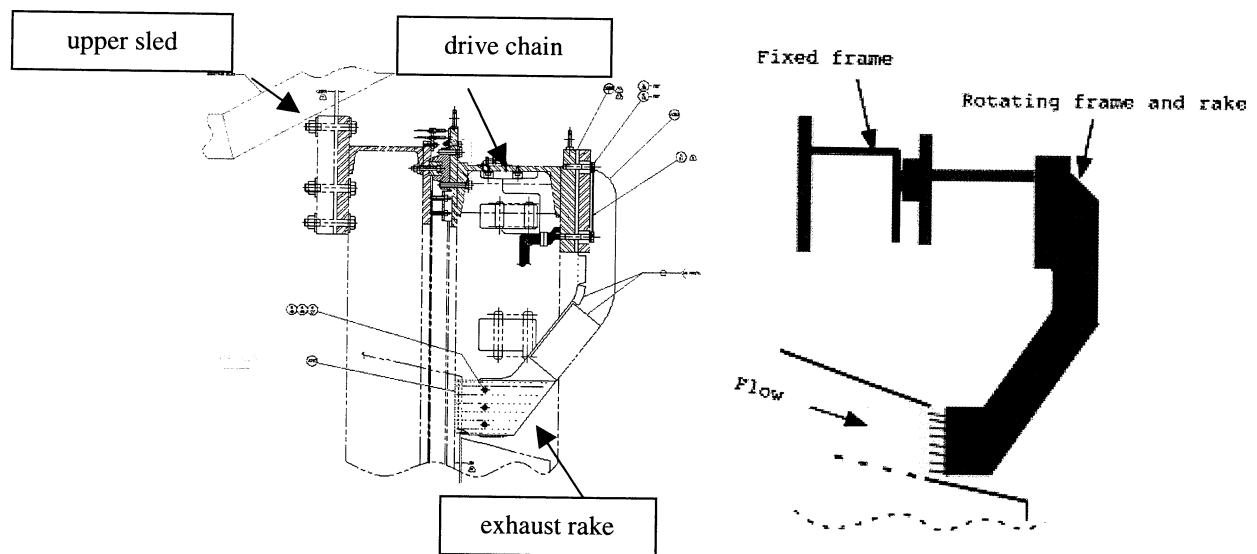


(b) Schematic side view of inlet rake assembly

Figure 2. Photographs of rakes installed on TFE731-60 engine



(c) Photographs of exhaust rake installed on TFE731-60 engine



(d) Schematic side view of exhaust rake assembly

Figure 2. Photographs of rakes installed on TFE731-60 engine (concluded)

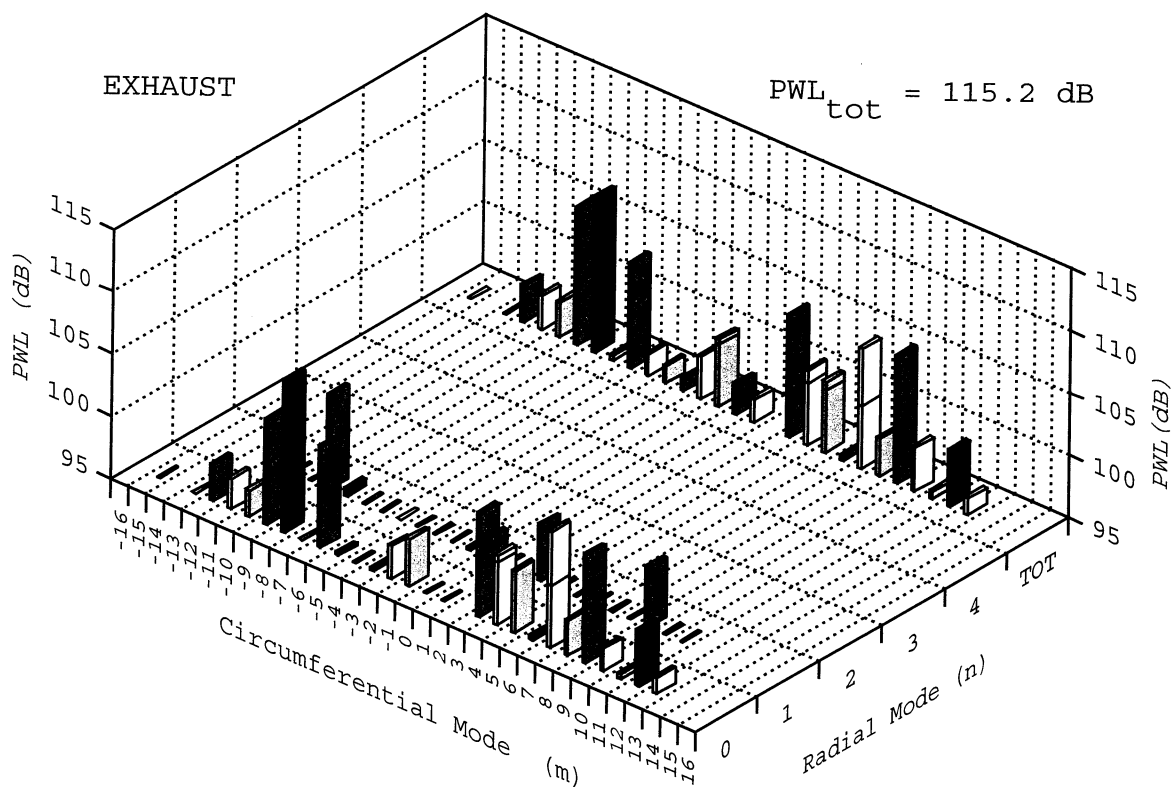
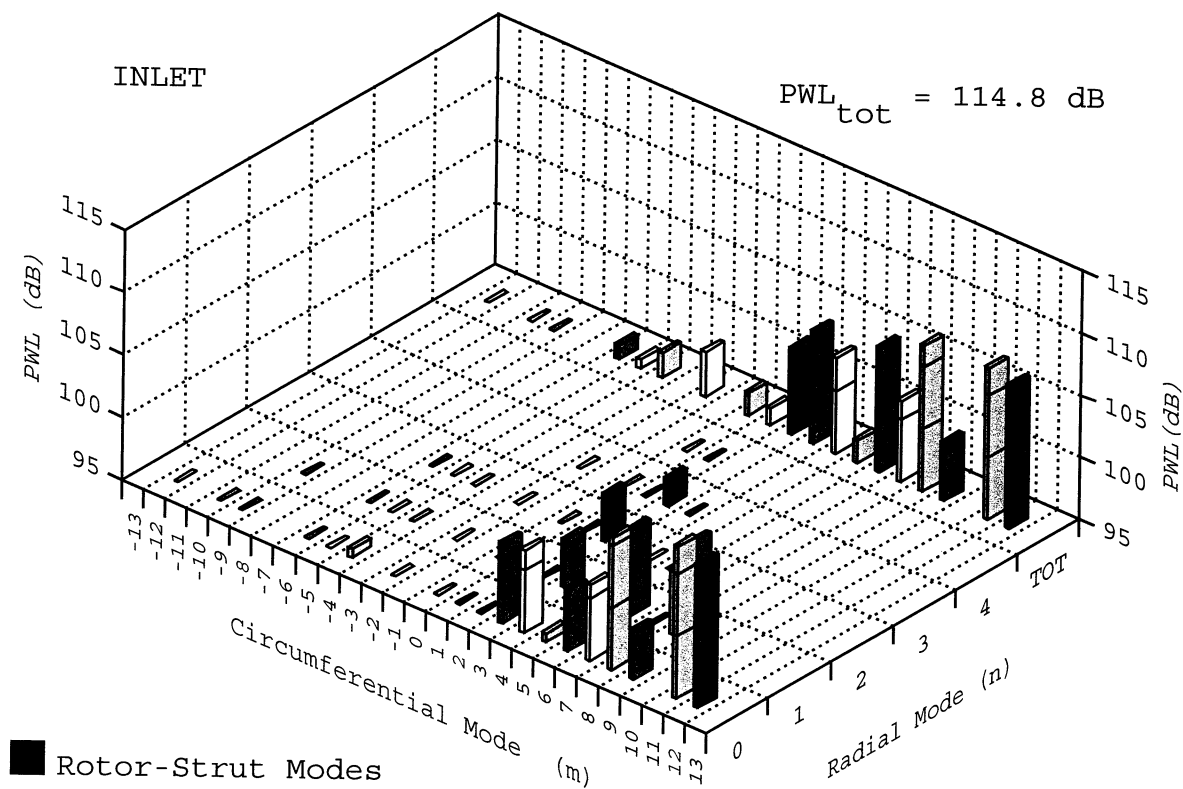


Figure 3. Mode map for 60% N1C, 1xBPF

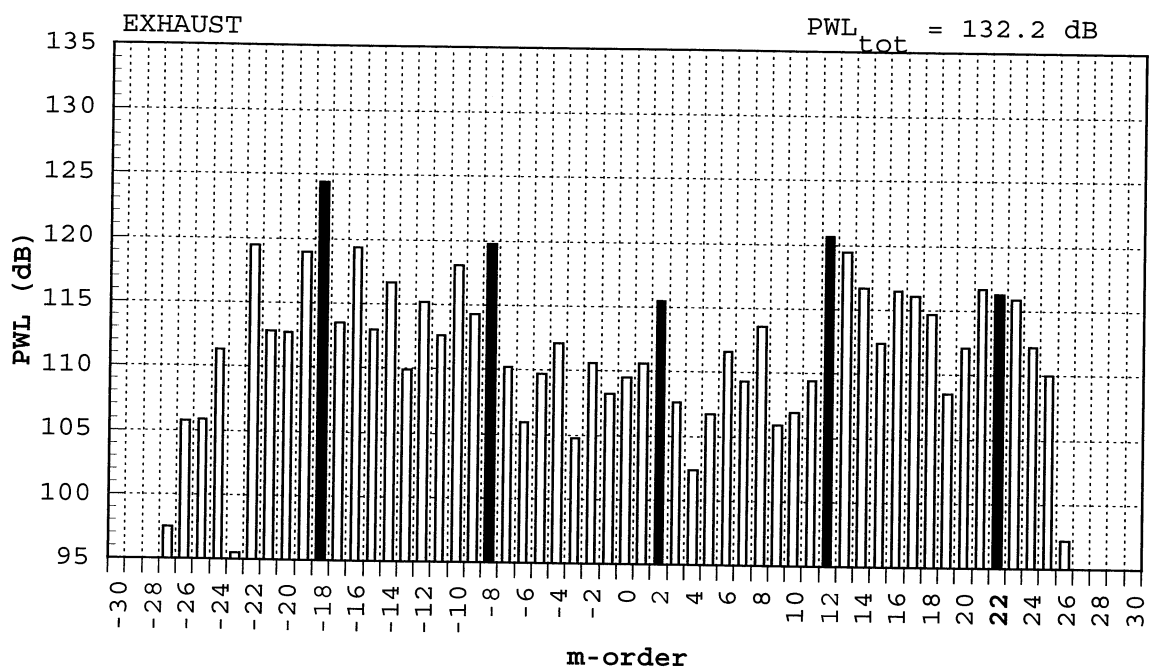
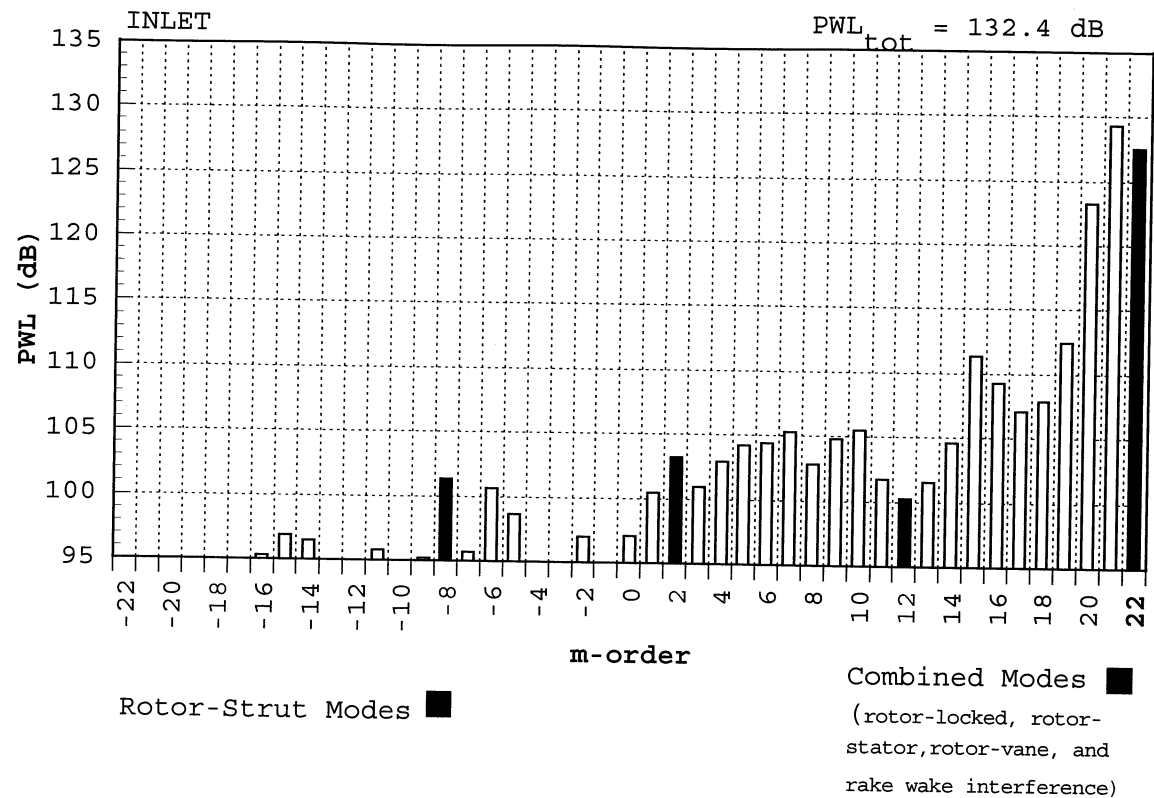


Figure 4. Mode map for 88% N1C, 1xBPF

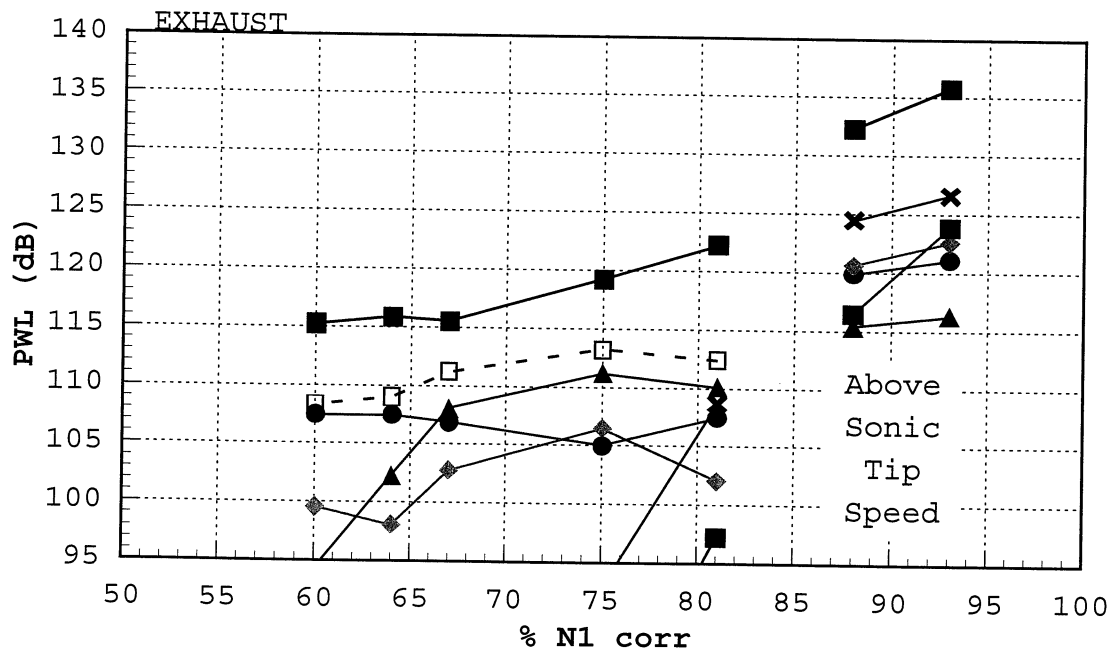
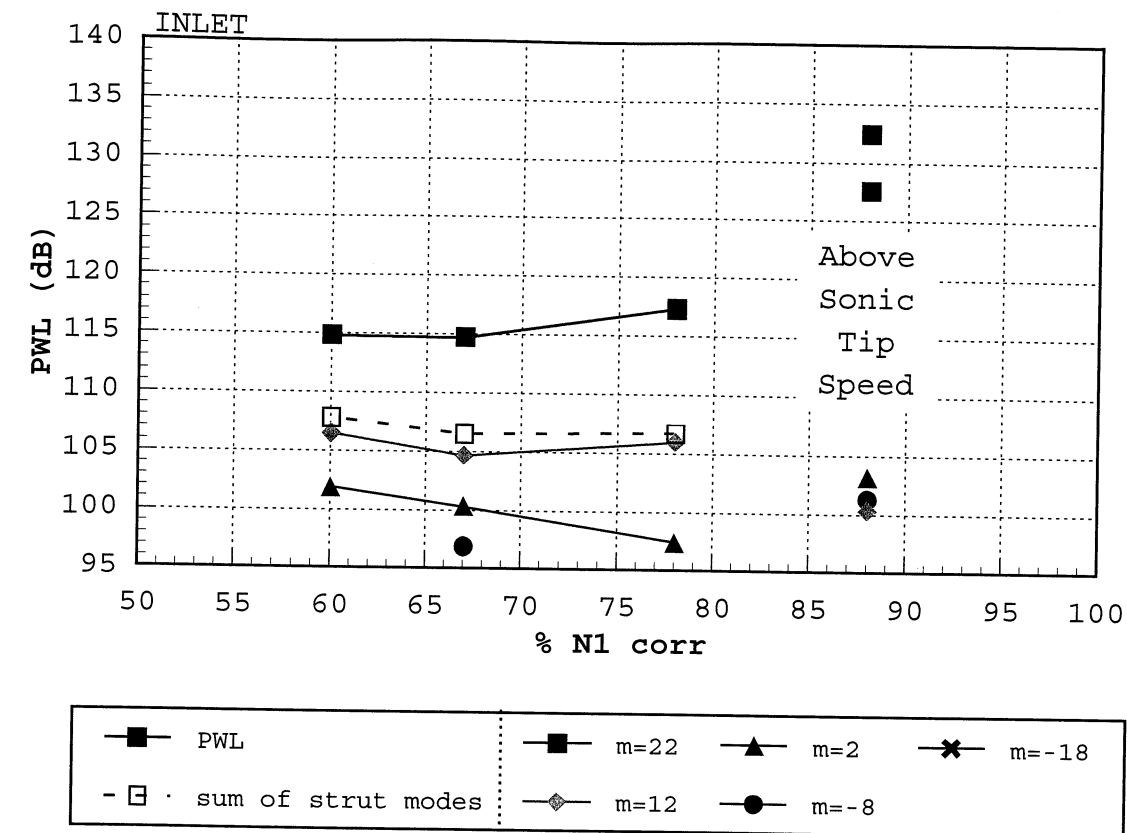


Figure 5. Total harmonic power versus corrected percent speed, 1xBPF

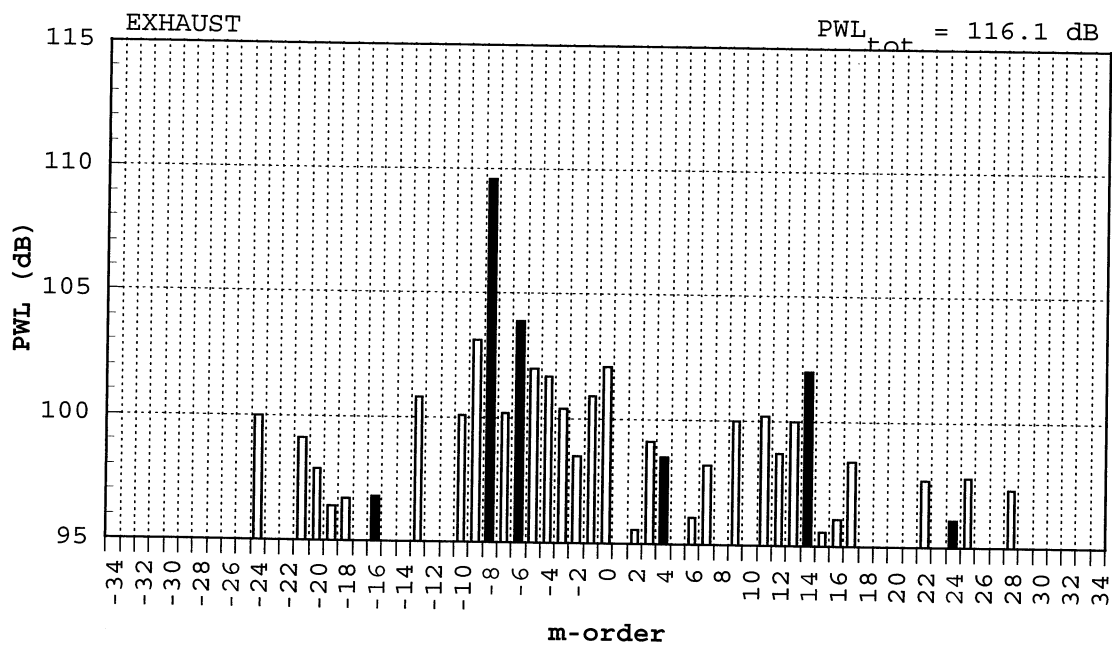
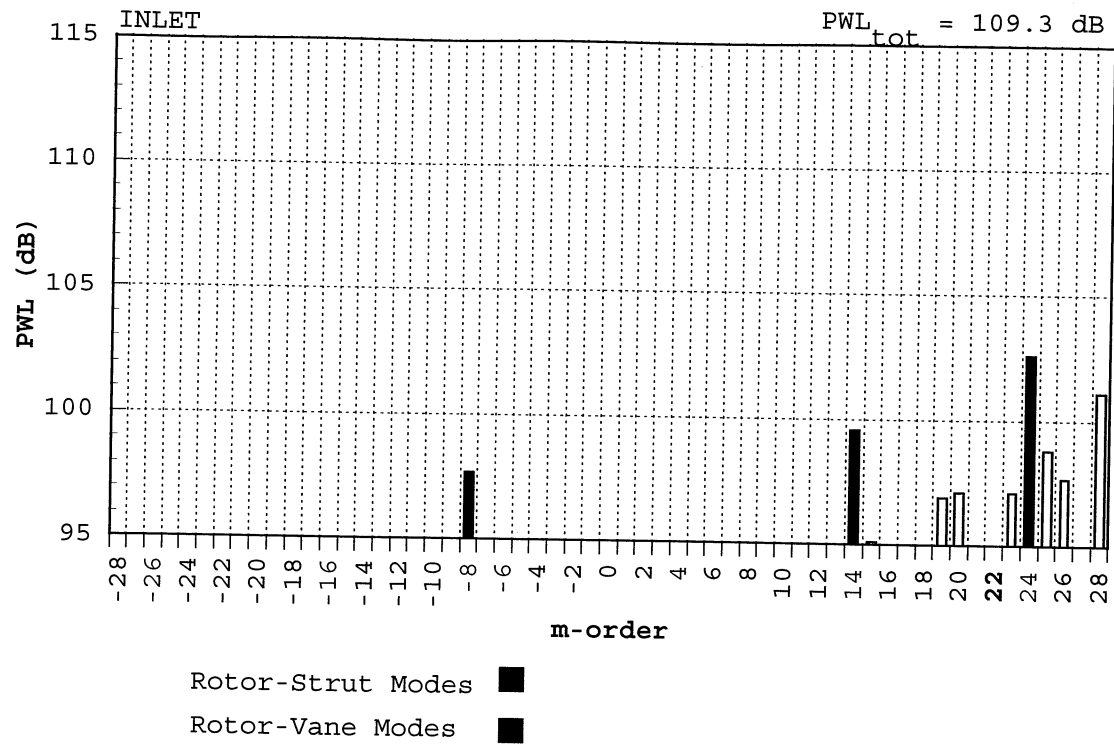


Figure 6. Mode map for 60% N1C, 2xBPF

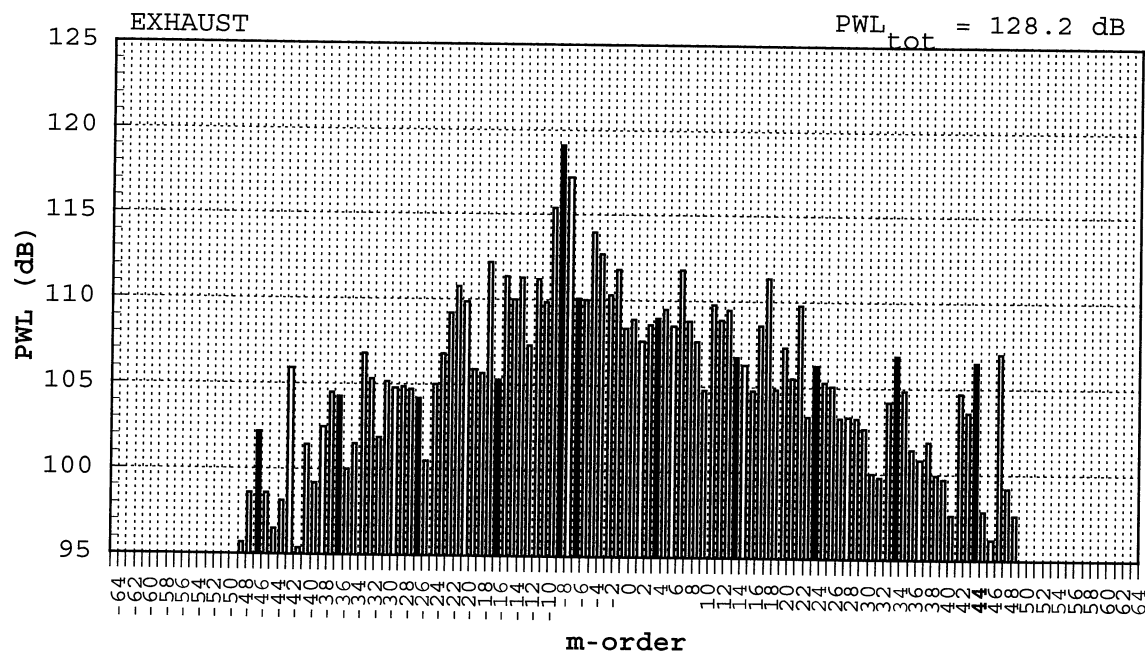
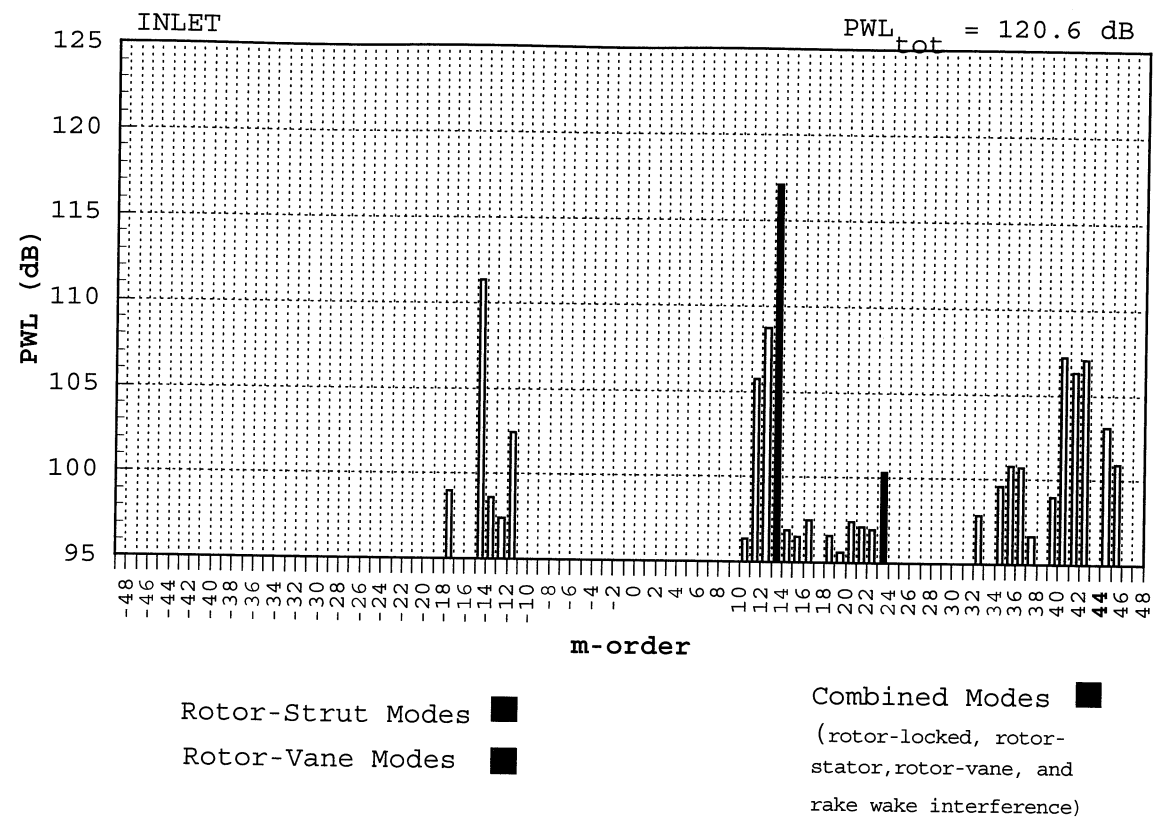


Figure 7. Mode map for 88% N1C, 2xBPF

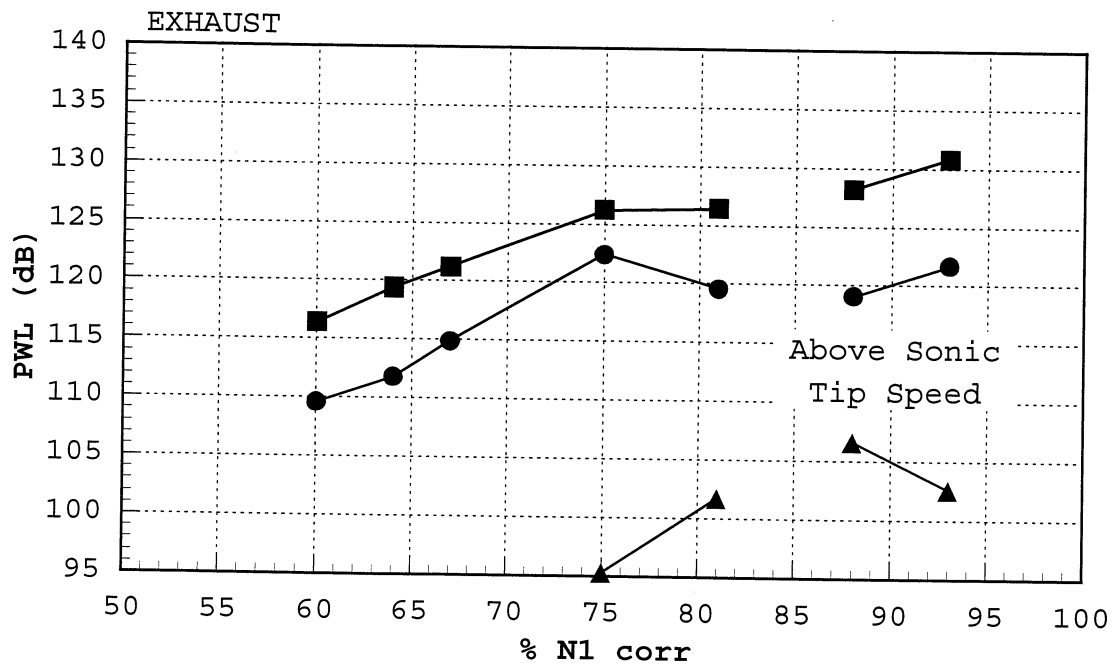
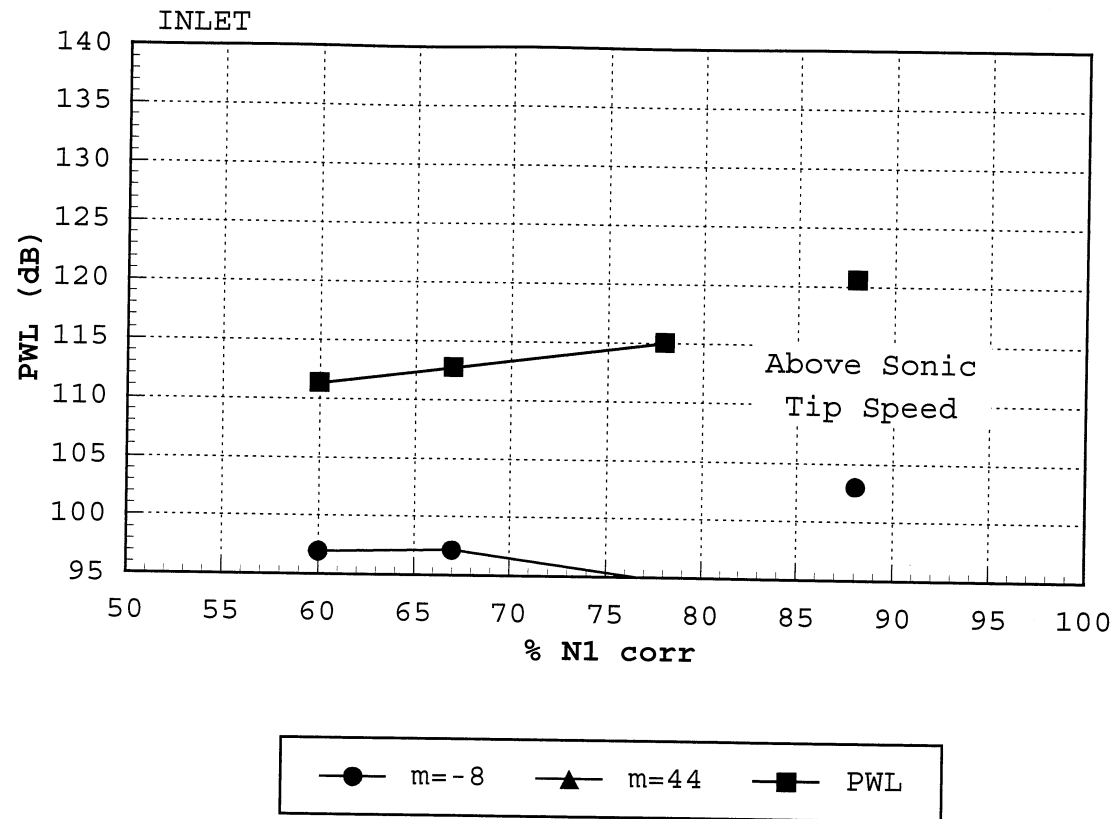


Figure 8. Total harmonic power versus NIC, 2xBPF

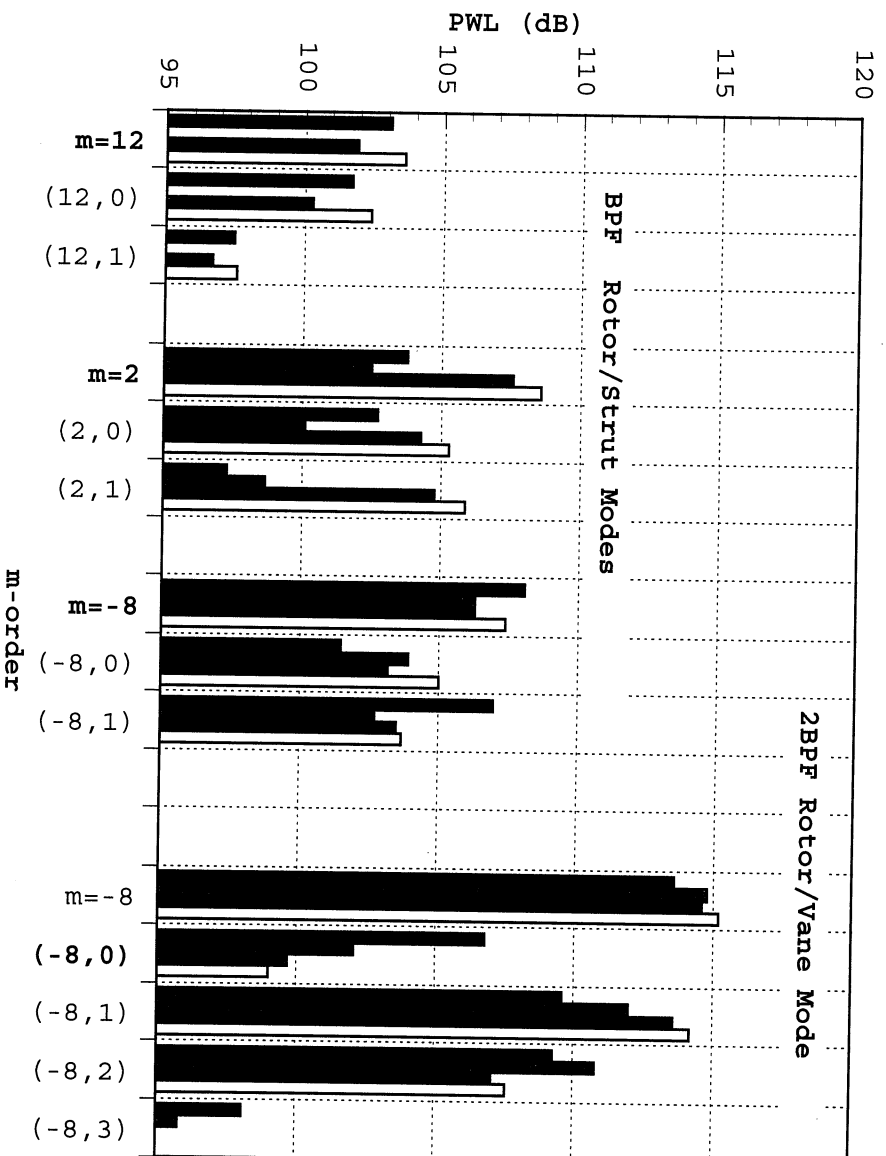
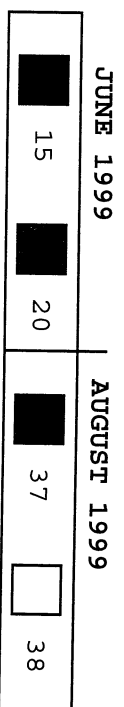


Figure 9. Repeatability of interaction modes in the exhaust (67% NIC)

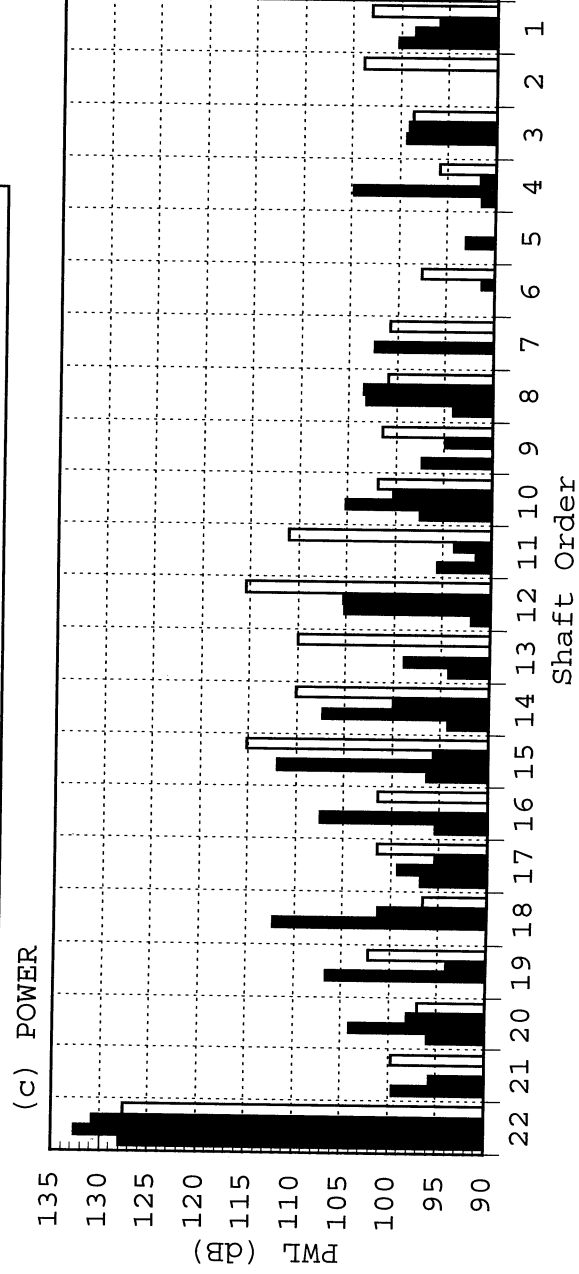
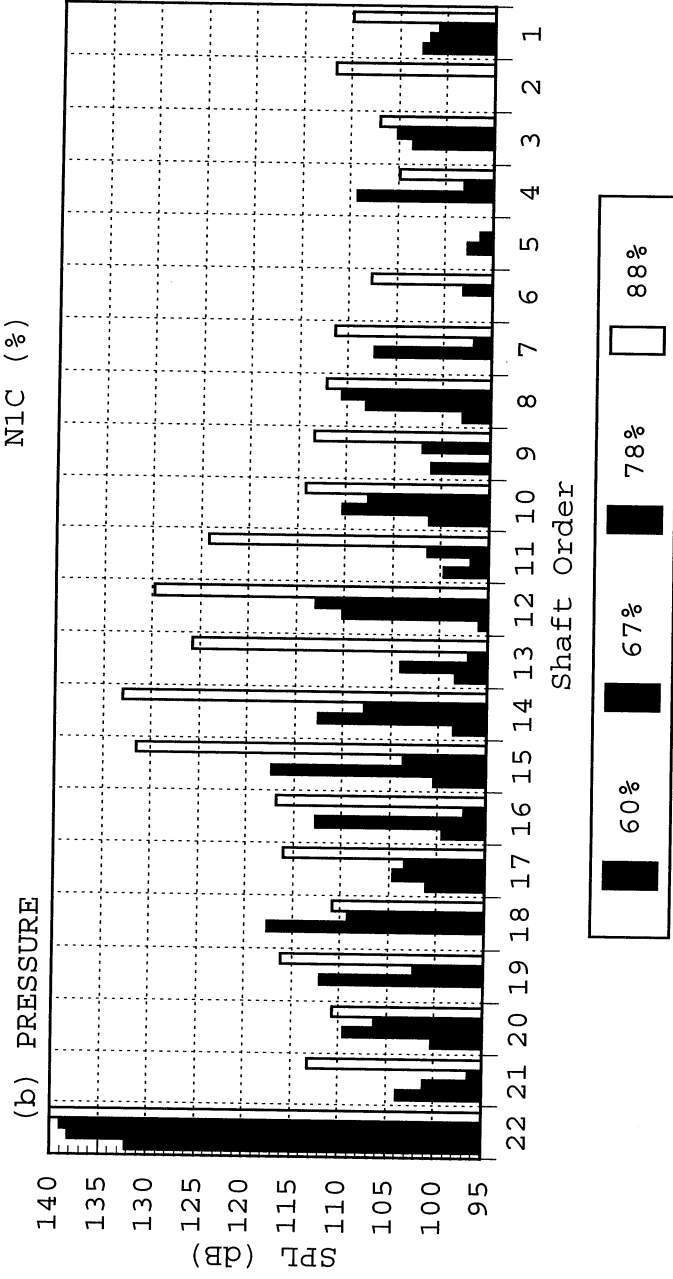
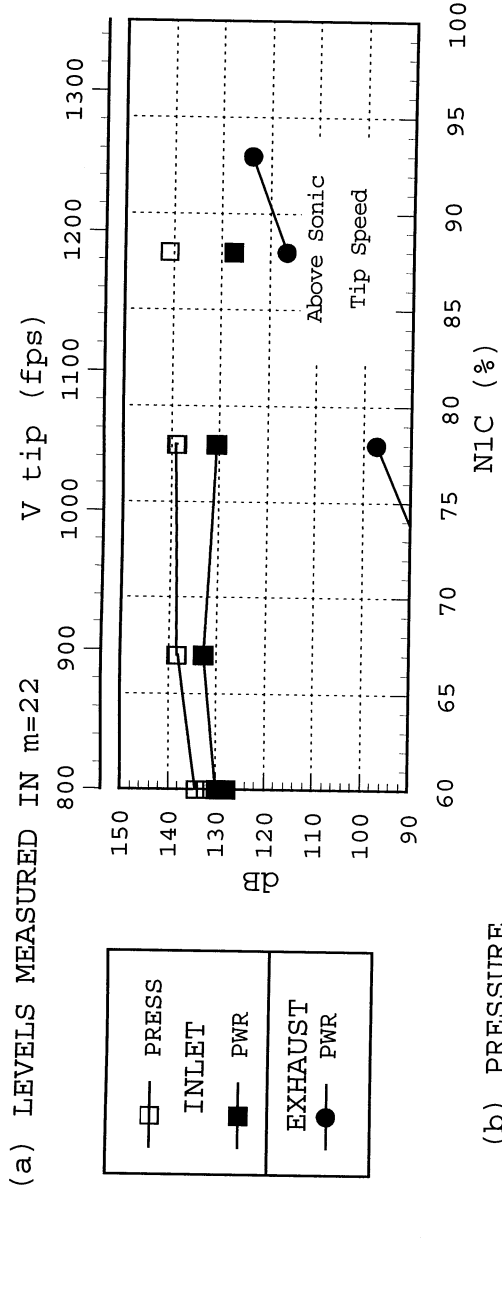


Figure 10. Shaft order analysis

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